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EMISSION CHARACTERISTICS OF BIDIRECTIONAL VORTEX COMBUSTORS OPERATING ON GASEOUS, LIQUID AND PULVERIZED SOLID FUEL[*]

Oleg Evdokimov[**], Alexander Guryanov, Sergey Veretennikov

Soloviev Rybinsk State Aviation Technical University, Rybinsk, Yaroslavl Region, Russia

Abstract

The paper reports on a comparison of emission characteristics in the bidirectional vortex combustor operating on different types of fuel. Gaseous propane, liquid kerosene, and solid pulverized peat are suggested. It is shown that emission curves differ from classical ones corresponding to gas turbine combustion. Comparative analysis of the emission curves shows that NO_x emission is similar for all three fuel types whereas CO emission differs significantly. The use of all types of fuel gives minima of CO emission for lean combustion. However, optimal ranges for solid and liquid fuel are smaller than for gas because of the strong influence of evaporation and devolatilization processes. Additionally, there is an increase in CO emission for kerosene and peat above the upper limit of the optimal λ range which corresponds to the most environmentally friendly combustion. CO emission for gaseous fuel remains minimal up to the lean flameout boundary.

Keywords: bidirectional vortex combustor, combustion, emission, gas, kerosene, pulverized solid fuel

1. Introduction

The combustion of hydrocarbon fuels in the combustion chambers of engines and burners leads to the formation of air-polluting compounds, the most toxic of which are carbon monoxide CO and nitrogen oxides NO_x (Warnatz et al., 2010). The concentrations of these pollutants in the exhaust gases depend significantly on the uniformity of the distribution of fuel and oxidizer in the combustion zone which determines the local values of air-fuel equivalence ratio λ and reaction temperature (Lefebvre and Ballal, 2010). As an example, we can consider a dependence of CO and NO_x concentrations on λ in the

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[**] Corresponding author: email: yevdokimov_oleg@mail.ru

combustion chamber of the gas turbine engine shown in Fig. 1. Data for the graph is taken from (Lefebvre and Ballal, 2010) and is related to inlet temperature and pressure to the combustion chamber equaled 573 K and 0.76 MPa.

As can be seen, the curve of CO concentration has a minimum corresponding to the value of 60 ppm at λ value close to stoichiometric λ = 1. This value of CO concentration meets the emission requirements of the ICAO and local (including Russian) standards. On the other hand, the area of the noted values of the air-fuel equivalence ratio λ is characterized by the maximum values of the curve for NOx concentration which reaches a value of 400 ppm. It is unsatisfactory for both aviation and energy. This fact makes it relevant to implement non-stoichiometric combustion technologies which define a significant reduction of nitrogen oxides formation as well as give high values of overall combustion efficiency.

Until recently, there were two main technologies of organizing non-stoichiometric combustion – are RQQL (Rich Burn-Quick Quench-Lean Burn) and LPP (Lean-Premixed-Prevaporated combustion) (Khosravy el_Hossaini, 2013). Both have at least two separate combustion zones and the difference between them is the following. RQQL technology has a rich primary combustion zone whereas LPP is based on preliminary mixing of components before combustion. Currently, there are many modifications and combinations of these technologies developed by large industrial companies: DLN (Dry Low NO_x), SAC (Single Annular Combustor), DAC (Dual Annular Combustor), TAPS (Twin Annular Premixing Swirler), RCL (Rich Catalytic Lean-burn), TVC (Trapped Vortex Combustion), and IGCC Gas Turbines (Integrated Gasification Combined Cycle) are among them (Liu et al., 2017).

An analysis of modern combustion technologies applied in aviation and energy shows that one of the promising ways to improve process efficiency is flow swirling (Gupta et al., 1984). There are a great number of studies devoted to swirl influence on combustor parameters and the sense of these works is that flow swirling significantly improves mixing and combustion efficiency as well as reduces weight and size of the combustion chamber (Alekseenko and Okulov, 1996; Syred and Beér, 1974). However, such a property of swirling flow as the formation of bidirectional flow is not common and used much less frequently.

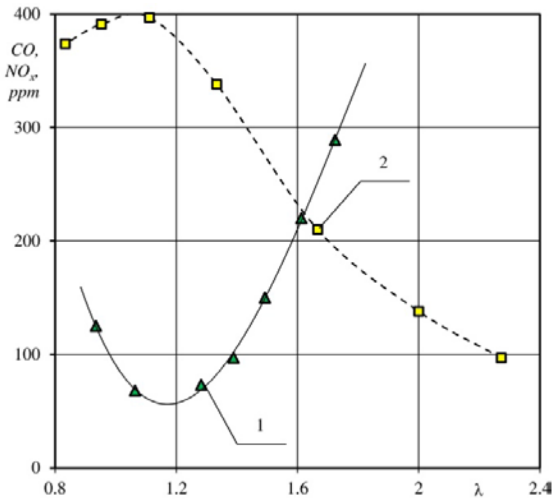


Fig. 1. The dependence of CO and NO_x emission on the air-fuel equivalence ratio λ (Lefebvre and Ballal, 2010): 1 – CO emission; 2 – NO_x emission

Bidirectional swirling flow occurs when an annular vortex moves toward the headwall of the domain, and then it moves in opposite direction as an inner core vortex, i.e. the flow is directed toward the end wall. A device where this kind of flow occurs is named as bidirectional vortex combustor. There are some important advantages of bidirectional combustors. They are related to combustor walls cooling, an additional increase in mixing quality, and formation of large-scale vortex structures that are necessary for the implementation of reliable ignition. Bidirectional vortex combustors are now applied as small-size rocket engines (Chiaverini et al., 2003; Gongnan Li et al., 2013; Yu et al., 2016), power plant combustion chambers (Benmenine and Bentebbiceh, 2018; Guryanov et al., 2020; Matveev and Serbin, 2012; Sudhakar Reddy et al., 2007), and igniters (Piralishvili and Guryanov, 2008).

Another important issue related to bidirectional combustors operation is an increase in fuel residence time which leads to combustion improvement and reduction of pollutant emission. Papers published on this topic show that fuel particles have residence time inside the bidirectional combustor at least twice more than in swirl burner (Dehghani et al., 2009; Evdokimov et al., 2019, 2020a, 2020b; Maicke and Majdalani, 2015).

Finally, one of the most interesting issues is fuel type burnt in the bidirectional combustor. Recent studies show that gaseous, liquid and pulverized solid fuel can be efficiently used in bidirectional combustors as well as high values of combustion efficiency can be achieved (Guryanov et al., 2017; Knuth et al., 2002; Mikhailov and Evdokimov, 2020; Piralishvili and Guryanov, 2008). However, we assume that the type of fuel strongly affects emissions. Therefore, the present paper is devoted to a comparison of the emission characteristics for the same bidirectional vortex combustor operating on different fuel types: gaseous, liquid, and pulverized solid fuel.

The main goal of this research is to study the emission characteristics of the bidirectional vortex combustor operating on gaseous, liquid, and pulverized solid fuel and find the most effective conditions for environmentally friendly combustion.

To achieve this goal, we analyze special features of combustion in the bidirectional vortex combustor and find out the influence of fuel type. This analysis is based on flame visualization as well as a comparison of CO and NO_x emission characteristics for gaseous, liquid, and pulverized solid fuel.

2. Materials and methods

The bidirectional vortex combustor which was used to study the combustion of different types of fuel is presented in Fig. 2. The fuel nozzle shown in Fig. 2 is changeable to supply the different fuel types – gaseous, liquid, and solid pulverized.

To give a comparison of the emission characteristics, this paper uses experimental data obtained earlier and published in (Guryanov et al., 2017) for gaseous propane, (Guryanov, 2007) for liquid kerosene, and (Evdokimov et al., 2020b) for pulverized peat. During all the experiments, the same setup was used. It consists of the following elements: a combustor, an ignition system, a fuel supply system, airlines, mass flow meters, gas analyzer, and a temperature measurement system. To measure NOx and CO emission Testo 350 XL gas analyzer was used, its uncertainty does not exceed ±10%. To reduce random measurement errors, each measurement was performed at least 5 times.

All the emission values were analyzed using the following dimensionless parameter: air-fuel equivalence ratio λ which formula is

$$\lambda = \frac{M_{\text{air}}}{M_{\text{fuel}} \cdot L_0} \ , \qquad (1)$$

where M_{air} is the air mass flow rate, M_{fuel} is the fuel mass flow rate, L_0 is the stoichiometric coefficient.

3. Results and discussion

The experimental research showed that both CO and NO_x emissions strongly depend on air-fuel equivalence ratio λ. Therefore these results are presented as λ dependences in Fig. 3-5. CO emission values are plotted on the primary vertical axis, NO_x emission values are plotted on the secondary axis.

An analysis of the results for gaseous fuel (Fig. 3) shows that the maximum values of the emission of both pollutants correspond to fuel-rich combustion as well as the stoichiometric case.

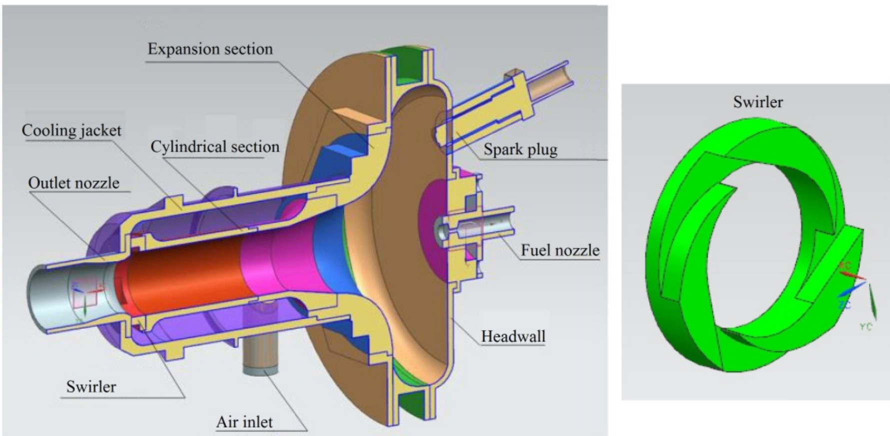


Fig. 2. Bidirectional vortex combustor

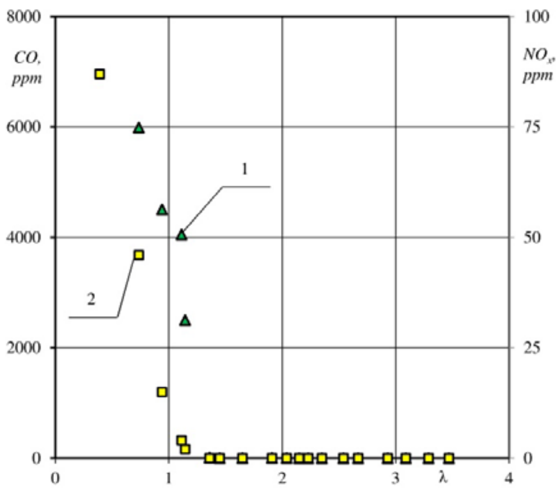


Fig. 3. The dependence of CO and NOx emission on the air-fuel equivalence ratio λ for gaseous fuel (propane): 1 – CO emission; 2 – NO_x emission

This fact is related to a significant ejection of atmospheric air into the combustion zone because of the lack of oxidizer at these operating modes. It leads to the formation of local high-temperature zones where thermal NO is formed as well as poor mixing efficiency which defines a significant underburning and CO emission.

It also should be noted there is almost no emission of both carbon monoxide and nitrogen oxides at the operating modes $\lambda > 1.4$. This fact can be explained by an increase in residence time at these modes. Thus, residence time becomes enough to provide complete fuel burnout even at a low temperature corresponding to lean values λ. At the same time decrease in temperature leads to reducing NO_x emission.

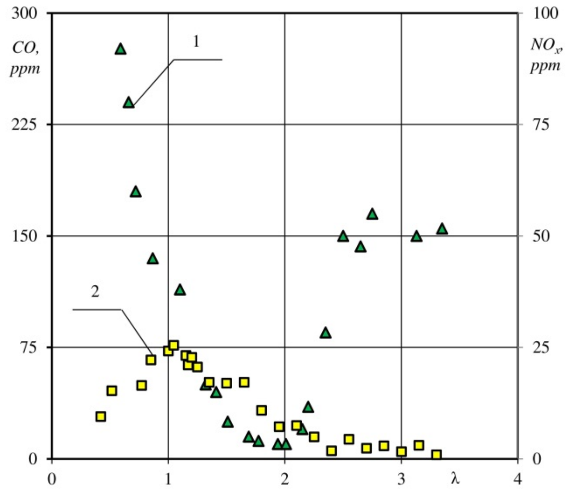


Fig. 4. The dependence of CO and NOx emission on the air-fuel equivalence ratio λ for liquid fuel (kerosene): 1 – CO emission; 2 – NO_x emission

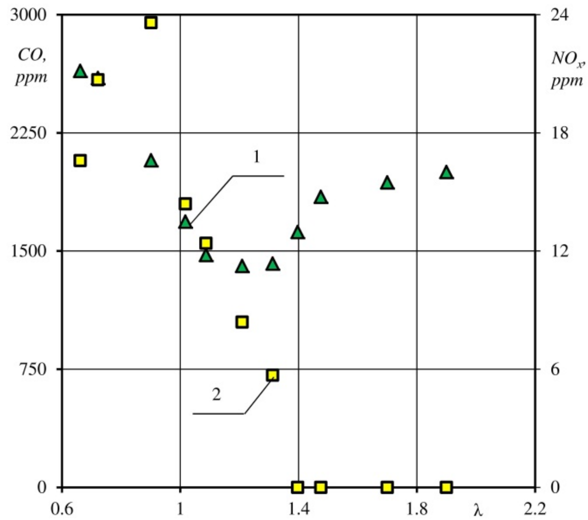
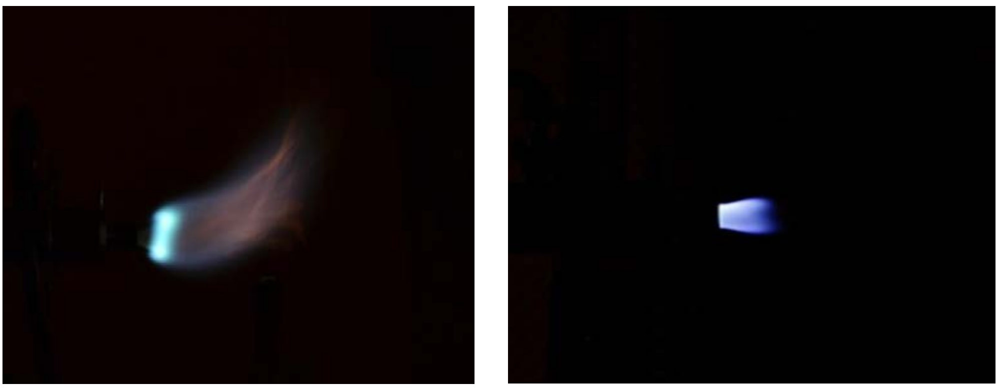


Fig. 5. The dependence of CO and NOx emission on the air-fuel equivalence ratio λ for solid fuel (pulverized peat): 1 – CO emission; 2 – NO_x emission

Combustion of liquid and pulverized solid fuel is a heterogeneous process. It requires additional time for droplets evaporation when kerosene is burning as well as for particle devolatilization when peat is used as a fuel. Moreover, noted processes require maintaining a high temperature for their implementation. Therefore CO curves shown in Fig 4 and 5 differ from one shown in Fig. 3. As can be seen, both curves have a minimum corresponding to the most environmentally friendly combustion and a further increase in the air-fuel equivalence ratio leads to an increase in CO emission. This is due to a decrease in temperature and slowing down the processes mentioned above. At the same time, NO_x curves are similar enough for all three types of fuel.

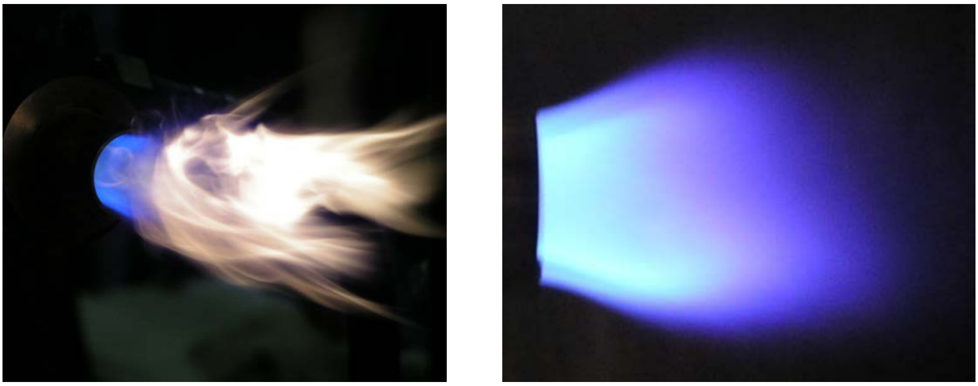
Another thing that should be noted is related to the air-fuel equivalence ratio corresponding to the minimum value of CO emission for studied types of fuel. The optimal ranges of λ are: for gas $1.3 < \lambda < 3.5$; for kerosene $1.5 < \lambda < 2.2$; for pulverized peat $1.1 < \lambda < 1.4$. Obviously, the smallest optimal λ range for solid fuel is related to its thermophysical properties discussed in detail in previous papers (Mikhailov et al., 2016, 2017, 2019) as well as the need to provide a definite terminal velocity (Evdokimov et al., 2020c). During experiments with pulverized peat, two air flows (primary and secondary) were supplied into the combustor: primary one was supplied through the swirler and the secondary one was supplied through fuel nozzle. Such change affected the flow structure inside the combustor which was the reason for decrease in λ optimal value.

Figures 6-8 show the photographs of the combustion process for used types of fuel at rich ($\lambda = 0.4$) and lean ($\lambda = 1.3$) operating modes. Colors and locations of flame confirm conclusions made above related to the most environmentally friendly modes. Lean modes are characterized by the combustion process which takes place almost completely inside the combustor. Rich modes are accompanied by a significant ejection of the atmospheric air into the combustion zone which is located outside the combustor.



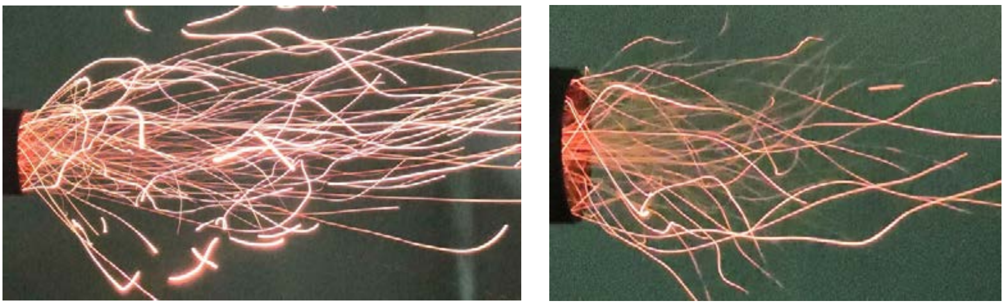
(a) (b)

Fig. 6. The photographs of the combustion of gaseous fuel at rich (a) and lean (b) operating modes



(a) (b)

Fig. 7. The photographs of the combustion of liquid fuel at rich (a) and lean (b) operating modes



(a) (b)

Fig. 8. The photographs of the combustion of solid fuel at rich (a) and lean (b) operating modes

4. Conclusions

The studies of combustion of different types of fuel in the bidirectional vortex combustor showed that there are both similarities and differences. NO_x curves for all three types of fuel are similar: the maximum values correspond to rich and near-stoichiometric combustion whereas lean combustion gives almost zero NO_x emission. On the other hand, CO emission strongly depends on fuel type because it is influenced by mixing quality and flow structure a lot. The optimal ranges of λ in terms of CO emission are: for gas $1.3 < \lambda < 3.5$; for kerosene $1.5 < \lambda < 2.2$; for pulverized peat $1.1 < \lambda < 1.4$. They all correspond to lean combustion and not to near-stoichiometric one as it can be observed for the classical gas turbine combustion shown in Fig. 1. However, the processes of evaporation and devolatilization for liquid and solid fuel respectively strongly affect temperature distribution inside the combustor at lean operating modes and define an increase in CO emission after $\lambda = 2.2$ for kerosene and $\lambda = 1.4$ for pulverized peat. At the same time, Co emission for gas fuel remains almost zero up to the flameout limit which corresponds to $\lambda = 3.5$.

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